Sedimentology and Holocene stratigraphy of Leschenault Inlet

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Abstract

Leschenault Inlet, a shallow estuarine lagoon, is separated from the Indian Ocean by a dune barrier, with the Collie and Preston Rivers discharging to its south. Geomorphic units and their related sediments in this system include: a central basin underlain by burrowed mud; a northern basin underlain by root-structured mud; an eastern platform underlain by sand; a western platform underlain by sand; muddy sand and mud, high-tidal platforms underlain by root-structured mud; spits and bars-and-lagoons underlain by sand, muddy sand, mud, and peat; pocket beaches underlain by sand and shell grit; and the Collie River and Preston River deltas, underlain by complex arrays of sand, muddy sand, mud and peat. The lithology and sedimentary structures of the sediments are related to their formative sedimentary environment due to several factors; firstly, the nature of the shores that provide reworked material (*e.g.* quartz sand ridges of the east shore *vs* quartz and carbonate sand ridges of the west shore); secondly, local hydrodynamics (*e.g.* below wave base and thus mud-accumulating, as in the central basin; or predominately wave agitated and hence mud-free sand, as in the eastern platform); thirdly, the distribution of biota as related to the environmental conditions; and fourthly, the effects of local biota. The large scale sedimentary patterns and Holocene stratigraphic relationships in this area are relatively simple. A shore-parallel wedge of sand reworked from Pleistocene landforms is onlapped by basin mud of the central estuarine lagoon. A shore-parallel linear barrier dune complex bars and retrogrades over sediments of this estuarine lagoon. Deltaic complexes invade the southern estuary, with the Collie delta recording a deltaic sand wedge capped by muddy sediments, and the Preston River delta recording a tidal-deltaic system of shifting shoals, and intervening mud deposits. At smaller scales, in contrast to the Pleistocene-based landforms of the eastern shore, and hence simple stratigraphy, the west coast of the estuary with its dynamic barrier dunes and staggered dune encroachments has more complex stratigraphic relationships between dune sand and estuarine sediment. Also at smaller scales, the deltas consist of layered sand, muddy sand and mud in upper deltaic sequences, shoestrings of sand (cheniers) interspersed with muddy sediments, and ribbon and shoestrings of mud.

Sea level has been variable in the region over the Holocene. Relative sea level was 2-3 m lower than present between 7 000-4 500 years BP, rising rapidly to a relative position 3-4 m higher than present between 4 500 and 3 500 years BP, and progressively falling to its current level from *ca* 2 800 years BP to the present. These sea level fluctuations had an effect on sedimentation and the development of sedimentary suites and coastal landforms, particularly in their placement in relationship to current MSL.

Keywords: sedimentary, Holocene stratography, Leschenault Inlet, estuary, south-western Australia.

Introduction

As an estuarine lagoon in south-western Australia, Leschenault Inlet presents a regionally unique situation (Fig 1). It is the only estuary along this coast that has formed behind a shore-parallel barrier dune complex, and since all the other major estuaries in the southwest region have a Pleistocene ancestry, it is the only estuary that is wholly Holocene in age (*cf* the Peel-Harvey estuary, Semeniuk & Semeniuk 1990). For a small estuary, Leschenault Inlet exhibits quite a range of sedimentary environments with associated distinct sediment types. This is because there are various source types for the sediments, a range of sedimentary particles formed within the system, and a range of formative sedimentary environments and sedimentary processes operating therein.

Few estuaries along the south-western coast of Western Australia have been comprehensively described sedimentologically (*cf* the Peel-Harvey Estuary; Brown *et al*. 1980; Semeniuk & Semeniuk 1990), and as part of the collected papers on the estuarine environment of Leschenault Inlet, this paper describes the sedimentology and stratigraphy of the estuarine environment to provide an understanding of the general evolution of the estuary and the development of estuarine sedimentary suites, and to understand the processes that led to the development of the estuarine wetlands that are peripheral to the system. As such this paper provides a geohistorical framework to understanding the sedimentological development and distribution of estuarine geomorphic units throughout Leschenault Inlet that are fundamental to the development of peripheral wetland and general estuarine habitats, and relates the sedimentological evolution of the system to the Holocene sea-level history.

In this paper, the Leschenault Inlet environment is described largely in terms of its components as though there had been no anthropogenic modification of the system. Sedimentation induced by anthropogenic effects, *viz* flood tidal delta accretion, and diverted river delta accretion is briefly mentioned in context, but not described in detail.

Methods

Aerial photographs taken between 1941 and 1998 were used to document changes in the estuarine shoreline and the evolution of small scale geomorphic features. Transects through selected geomorphic units were established to describe sediment types and stratigraphy (Figs 3-7). In total some 200 sites were drilled or cored. Onshore stratigraphy was determined by drilling with a reverse-air-circulation corer to depths of 30 m, and augering and trenching to shallow depths of 1-2 m. Subaquatic stratigraphy deeper than 2 m was determined by probes and water jetting core excavation. Cores 1-2 m long were obtained from subaquatic environments to document small scale sedimentary sequences, and short cores 20-30 cm long were obtained from the main sedimentary environments to document sedimentary structures. Cores were frozen and then split to expose the sedimentary sequence and structures. Sediments were collected from the surface from a wide range of sites across the estuary as described by Wurm & Semeniuk (2000).

Sediments in the stratigraphic sequence were described under a binocular microscope in terms of colour, fabric, texture and composition. Particle size and roundness descriptions are after Wentworth (1922) and Powers (1953). Selected sediments in replicate sites of the various sedimentary suites were wet-sieved through standard Endecott sieves at 1 ϕ intervals to determine grain size distribution. Shell retained on the 2 000 mm sieve was identified as to molluscan species to determine mollusc assemblages at a given sampling site. For selected samples corresponding to samples collected from the 22 sample sites of Wurm & Semeniuk (2000), mud that passed through the < 63 mm sieve was combusted at 550 °C and 1 100 °C to determine organic carbon and calcium carbonate content, respectively. Shell samples collected for radiocarbon analyses were cleaned, acid washed, dried and then wrapped in aluminium foil for transport to commercial laboratories. Note that the term "bar-and-lagoon" refers to a sand bar and accompanying lagoon system.

Regional setting and geohistorical context

Leschenault Inlet is largely a shallow estuarine lagoon located along the coast within the southern part of the Swan Coastal Plain (Semeniuk & Meagher 1981), and located in the Leschenault-Preston Sector of Searle & Semeniuk (1985). The estuarine lagoon is separated from the Indian Ocean and Rottnest Shelf by a barrier dune system, termed the Leschenault Peninsula (Semeniuk 1985). The estuary can be classed as a microtidal barrier lagoon estuary, according to Hayes (1975). Tides are microtidal and usually diurnal, with a maximum range of 0.9 m, and a prevailing range of 0.5 m.

The study area of Leschenault Inlet is located in a subtropical subhumid climate (Koppen 1936), or Mediterranean climate (Gentilli 1972); annual rainfall is *ca* 880 mm and annual evaporation is *ca* 1 980 mm (Anon 1975).

From east to west, the three main landforms bordering and constituting the Leschenault Inlet system are (Figs 1 & 2):

1. a high ridge of Pleistocene quartz sand and limestone, referred to the Mandurah-Eaton Ridge, and to the northeast, lowlands underlain by Pleistocene limestone referred to the Yalgorup Plain (Semeniuk 1995, 1997), both of which comprise the eastern hinterland;
2. Leschenault Inlet itself, which is a elongate shore parallel, shallow estuarine lagoon; and
3. a high quartz and carbonate sand dune barrier, the Leschenault Peninsula (Semeniuk & Meagher 1981), Holocene in age, that bars Leschenault Inlet.

In addition, two deltas, the Collie River Delta and the Preston River Delta, enter the estuarine lagoon to its southeast and south (Fig 1).

The form, internal features, and the shore types of the Leschenault Inlet environment have been determined by several factors: 1. the ancestral topography of the eastern hinterland (the Mandurah-Eaton Ridge and the Yalgorup Plain) in that the former provided quartz sand to the eastern platform, and the latter forms the basis of the low tidal limestone platform to the northeast; 2. the effects of a mid-Holocene higher sea level reworking the quartz sand of the Mandurah-Eaton Ridge; 3. orientation and longitudinal extent of the Leschenault Peninsula barrier dunes; 4. the eastward migrating parabolic dunes encroaching onto the west estuarine margin from the barrier dune complex; and 5. deltaic buildups at the Collie River and Preston River mouths.

Stratigraphic framework

The stratigraphy of Leschenault Inlet area has a bearing on the types of geological materials that frame the estuary and that have been or presently are available for erosion and distribution as sediments into the environment. The main stratigraphic units in the area (after Semeniuk 1983, 1995) are discussed in Table 1.

Holocene units are shown diagramatically in Fig 2.

Source of sediment types

There are 8 main sources of sedimentary particles that contribute to the sediment types in Leschenault Inlet. These are:

1. quartz sand derived allochthonously by erosion from the ridge of Eaton Sand along the eastern shore of the estuarine lagoon; this tends to be fine to medium and moderately rounded;
2. quartz and carbonate sand derived allochthonously from the Holocene barrier dunes, by wave erosion along the western estuary shore, by transport into the estuary as mobile dunes, or transported by wind as a short range suspension deposit; this sand tends to be fine to medium and rounded; carbonate grains are skeletal debris of oceanic provenance (shell fragments, foraminifera) and limestone clasts;
3. quartz sand allochthonously injected into the estuary by the Collie and Preston Rivers flood waters; this sand tends to be fine to medium to coarse, and angular to moderately rounded;
4. phyllosilicate clay (kaolinite, smectite, halloysite, and some poorly crystalline clay), derived allochthonously

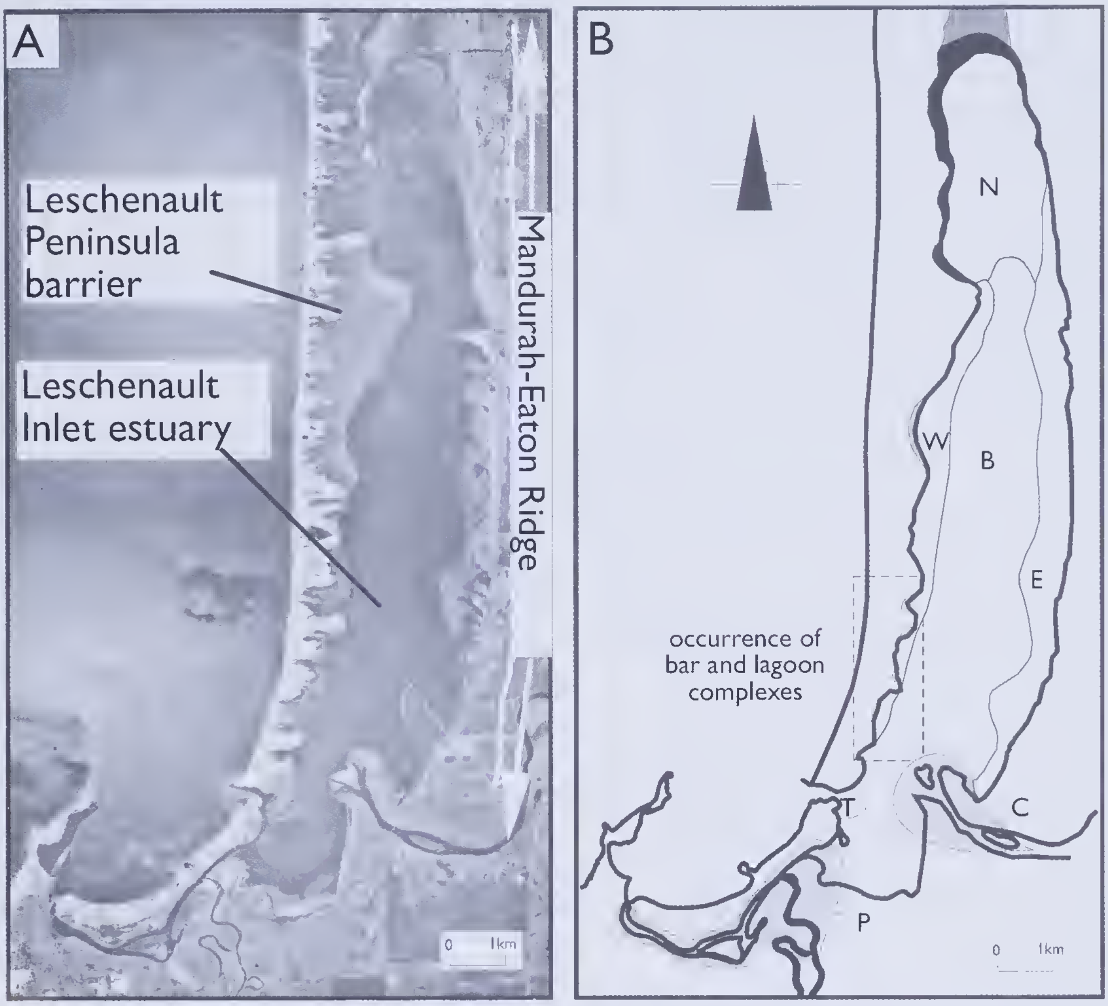

Figure 1. A: Aerial photograph of Leschenault Inlet show dune barrier of the Leschenault Peninsula, the elongate estuarine lagoon, the deltas, and the eastern shore of the Mandurah-Eaton Ridge. **B:** Map showing the geomorphic components of the Leschenault Inlet estuarine lagoon. N Northern Flat; B Central Basin; W Western platform; E Eastern platform; Supratidal flat; High tidal flat; C Collie River delta; P Preston River delta; Bar and lagoon complexes; T Tidal delta.

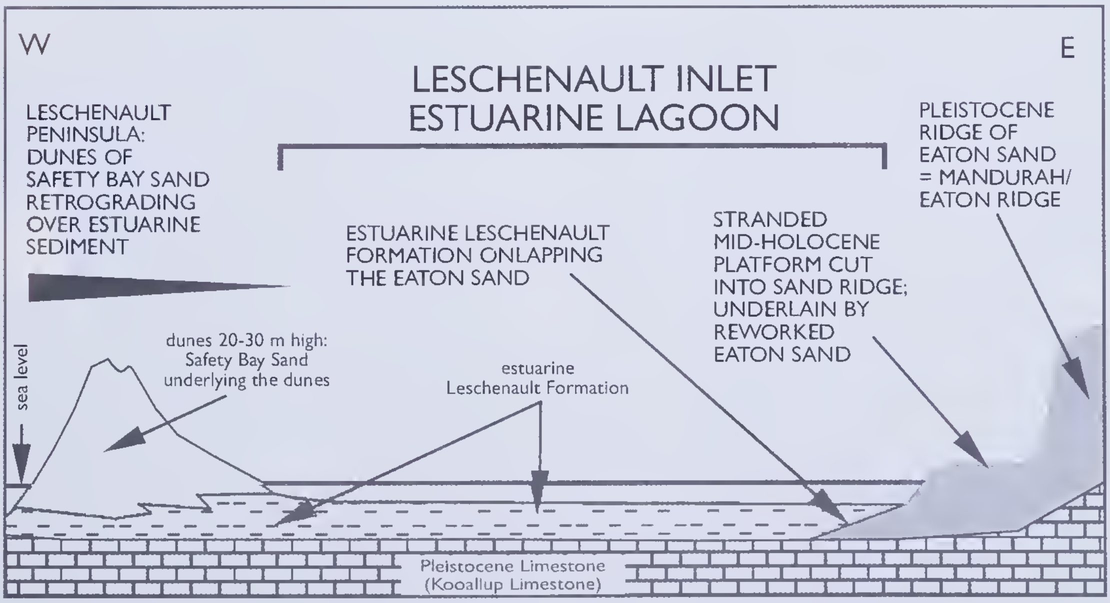

Figure 2. Holocene stratigraphic and geomorphic framework of the Leschenault Inlet estuary.

Table 1. Stratigraphic units in the Leschenault Inlet area in order from youngest to oldest, their ages, and their contribution as a sediment source.

Stratigraphic unit	Age	Contribution to sedimentation in Leschenault Inlet
Leschenault Formation	Holocene	part of the modern sedimentation patterns in the estuarine lagoon
Safety Bay Sand	Holocene	source for sand for the western estuarine platforms
Eaton Sand	Pleistocene	source for sand for the eastern estuarine platforms
Kooallup Limestone	Pleistocene	none
Tamala Limestone	Pleistocene	none
Australind Formation	Pleistocene	as a marl, with exposure to the south of the estuary, this partly was a source of phyllosilicate clay for the Leschenault Formation
Leederville Formation	Tertiary	none
Bunbury Basalt	Cretaceous	as a weathered body, with relief above the estuarine basin, this partly was a source of quartz and phyllosilicate clay for the Australind Formation and the Leschenault Formation

either injected into the system by flood waters of the Collie and Preston Rivers, or eroded from the southern part of the area from the Bunbury Basalt and Australind Formation;

5. carbonate silt generated autochthonously within the estuarine lagoon by accumulation of foraminifera, or by breakdown of calcareous estuarine skeletons such as molluscs, crustacea, foraminifera, and hard parts of polychaetes, and other biota;
6. silica silt generated autochthonously within the estuarine lagoon by accumulation of marine and estuarine diatoms;
7. plant detritus grading to organic ooze, generated autochthonously within the estuarine lagoon by the breakdown of plant material; and
8. shell gravel and fragments generated autochthonously in the estuarine lagoon by the shelly benthic biota, and fragmented by benthic and nektonic scavengers and predators.

Analyses of < 63 mm fraction for selected sediments in the different sedimentary environments in terms of their organic carbon content, carbonate mud, and silicate (quartz silt and clay, phyllosilicate clay, and diatoms) are shown in Table 2.

X-ray diffraction of the acid-digested carbonate-free < 63 mm fraction, and subfractions 5-63 mm and < 5 mm, shows a range of minerals to be present in the silt and clay fraction. Kaolinite, smectite, halloysite, poorly crystalline clay, muscovite and some quartz are in the clay fraction, and plagioclase, K-feldspar and quartz mainly comprise the silt fraction.

The range of sedimentary processes and synsedimentary diagenetic processes that structure and alter the sediments include; burrow structuring and bioturbation by estuarine benthos and fish; layering formed by physical reworking; grain pigmentation by iron sulphide precipitation; local carbonate precipitation forming crusts in the tidal zone; current winnowing to develop shell lag laminae; reworking of mud cliffs to form local mud clast conglomerates/breccias; and storm transport of shell from subtidal and tidal environments into the high-tidal and supratidal.

Estuarine geomorphology, sedimentary environments and processes, and sediment suites

Geomorphology and sedimentary environments

The estuarine geomorphic units within Leschenault Inlet essentially corresponds with the main sedimentary environments that form the sediment suites in the area. Geomorphology thus forms a fundamental and logical framework to describing the sedimentology in the area. The estuarine geomorphic units in the area are (Fig 1); 1. the main central basin; 2. the northern basin; 3. the eastern platform; 4. the western platform/ramp; 5. high-tidal flat platforms; 6. low-tidal flats; 7. spits, and bar-and-lagoon shores; 8. pocket beaches; 9. the northern supratidal flat; 10. the Collie River Delta; and 11. the Preston River Delta.

The low-tidal flats, spits, pocket beaches, and bar-and-lagoon shores are too small in scale to be shown in Fig 1.

In addition, there are two sedimentary units formed as a result of anthropogenic activities: 1) a small fan-shaped flood tidal delta formed leeward of an artificial channel known as "The Cut", which was excavated to facilitate exchange between the ocean and the estuary; and 2) a small fan-shaped delta formed where the Preston River diversion now enters southern Leschenault Inlet.

The central basin within the estuarine lagoon is a long, shore-parallel relatively deeper water mud-floored depression (generally 1.5-2.0 m deep). The northern basin is an oval, shallow, mud-floored depression (generally 0.5-1 m deep), that grades upslope to the northern supratidal flat. The eastern side of the estuarine lagoon where it adjoins the hinterland shore is a shore-parallel narrow, shallow water sand platform (low tidal to 1.0 m deep), vegetated by the seagrass *Halophila ovalis*, lobed on its deep water margin and straight-edged on its landward side. The western side of the estuarine lagoon where it adjoins the barrier dune is a shallow water muddy sand platform or ramp (low tidal to 1.5 m deep), also vegetated by *Halophila* *ovalis*, with a lobed deep water margin and a multiple lobed shore as a result of the encroachment of parabolic dunes into the estuary; inter-dune shores are protected small embayments underlain by mud and muddy sand.

The geomorphic nature of the eastern and western platform and ramps, *i.e.* whether the deep water margin is steeply descending (*i.e.* the edge of a platform), or gently descending (*i.e.* a ramp), can be related to the longevity and stability of the shore. The eastern platform borders a long-term stable ridge, and has developed as a wave built structure, formed and stabilised over the later Holocene. The western platform/ramp borders a dynamic shore of mobile dunes. As a result, with variable influx of sand, and varying gradients along the shore, the deep water margin of the western structure varies from steep to gentle.

In the high-tidal zone, both east and west estuary shores are mainly of saltmarsh-vegetated high tidal platforms, underlain by mud or sandy mud, and commonly terminated by a small cliff. The width of these high-tidal platforms varies from narrow (5-10 m) to wide (> 500 m) depending on location in relationship to mobile dunes *i.e.* encroaching dunes shorten their width), erosional or depositional processes (*i.e.* estuarine coastal erosion shortens their width, and estuarine high tidal mud accretion causes platform progradation), and ancestral sand ridges.

Locally, on western high-tidal platforms, often bridging interdune corridors, there are low ridges (< 20 cm high) of mud behind which there are shallow lagoons or ponds. These mud ridges appear to be accretionary, formed by wave action reworking mud deposits of the high-tidal platforms into a shore-parallel feature. On the eastern shore, above the level of high tide, there is a stranded sand platform, whose surface and margin is marked by relict sand waves, low beach ridges, and cusps. In the low-tidal zone, in front of the small cliff cut into high-tidal platforms, there is generally a gently inclined to sub-horizontal vegetation-free low-tidal flat, underlain by sand or muddy sand or sandy mud.

Along the margin of the western shore, abutting or adjoining the parabolic dune projections, there are locally developed spits, and bar-and-lagoon shores. The spits emanate from eroding dune tips, forming low relief narrow sand bodies (generally 2-5 m wide, 0.5-1 m high) projecting onto the tidal zone or the estuary, generally traversing an interdune corridor or embayment depression. Where spits have encroached fully across an interdune corridor or embayment, the tidal embayment may be barred, and a bar-and-lagoon system is formed, with the lagoon tens of metres across. Recently formed spits and bars are vegetation-free; older forms are inhabited by terrestrial vegetation of coastal dune affinities. Lagoons are open water bodies, or vegetated with rushes or samphires.

A broad supratidal flat, nearly horizontal, to very gently inclined towards the estuary, emergent by progradation, underlain by mud, and colonised by samphire, borders the northern Leschenault Inlet. The flat extends the full width of Leschenault Inlet, and has prograded some 2 km.

The Collie River has built a fluvial-dominated, to wave-modified delta where it enters Leschenault Inlet. The delta

Table 2. Analysis of the < 63 mm fraction.

Sample site	% organic Carbon	% $CaCO_3$	% silicate mud clays and siliceous diatom	Comments
southern estuary western platform	13.89	15.91	70.20	dominated by phyllosilicate clays and silica; carbonate mud and organic detritus also contribute
middle estuary eastern platform	20.83	5.68	73.49	dominated by phyllosilicate clays, silica, and organic detritus; minor carbonate mud
middle estuary central basin	12.14	5.84	82.02	dominated by phyllosilicate clays and silica; minor carbonate mud and organic detritus
middle estuary western platform	16.77	6.16	77.07	dominated by phyllosilicate clays and silica; minor carbonate mud and organic detritus
northern estuary eastern platform	14.29	19.48	66.23	dominated by phyllosilicate clays and silica; carbonate mud and organic detritus also contribute
northern estuary central basin	15.89	8.66	75.45	dominated by phyllosilicate clays, silica, and organic detritus; minor carbonate mud
northern estuary western platform	15.00	6.82	78.18	dominated by phyllosilicate clays, silica, and organic detritus; minor carbonate mud
northern supratidal flat	7.48	1.46	91.06	dominated by phyllosilicate clays and silica; minor carbonate mud and organic detritus
Preston River Delta tidal flat	12.66	32.80	54.54	dominated by phyllosilicate clays and silica; carbonate mud and organic detritus also contribute

is digitate, with storm ridges developed within the subaerial deltaic plain on its northern part where it faces the northerly to northwesterly derived winter storms. The delta is comprised of delta-front sands, a bifurcating channel, mid-channel islands, abandoned (sediment-filled) channels, levees, sub-aerial marshy flats, and stranded beach ridges and cheniers. Sand, muddy sand, mud, and peat are the main sediments that underlie the delta.

The Preston River had built a tide-dominated delta where it enters Leschenault Inlet. This delta has been partly destroyed by engineering activities, but its remnant is composed of a complex of tidal-current-aligned shoals and emergent islands, with intervening shallow channels. The islands are vegetated by samphires, rushes, and mangroves in the tidal zone, and terrestrial vegetation in the supratidal parts. Sand, muddy sand, shelly sand and shelly muddy sand (where shells are estuarine derived), mud, and peat are the main sediments that underlie this delta.

Sedimentary processes

The Leschenault Inlet environment is protected from the Indian Ocean, and hence only wind generated effects (waves, currents, aeolian action), tidal currents, and river flood currents are important.

There are three main important wind directions that generate waves on the Leschenault Inlet water body (Semeniuk & Meagher 1981): summer afternoon sea breezes emanating from the southwest (driving waves to northern sectors, obliquely impinging on the eastern shores); summer morning land breezes, of lower intensity than sea breezes, emanating from east and southeast (the latter also drive waves to the north, obliquely impinging on the north-western shores); and winter storms deriving from the northwest and north (driving waves southwards). With a fetch of 10 km in Leschenault Inlet, summer sea breezes with sustained wind speeds of up to 15 m s^{-1} (though more typically 4-6 m s^{-1}) and winter storms with wind speeds of 10-15 m s^{-1} can generate appreciable and significant wave action on the shores and shallow water sediment bodies of Leschenault Inlet. Waves trains are not of sufficient height and wave length, however, to effect significant sediment mobility in the 1.5-2 m deep central basin.

Winds also generate wind-driven currents that transport fine sediment in suspension. As a result of the dominating northerly-directed wind system (both south-westerly derived sea breezes and south-easterly derived land breezes) there is a strong net northward wind drift in the estuary. Wind further mobilises estuarine shoreline beach sand, constructing small beach ridges and dunes.

Tidal currents are locally important, despite the fact that the system is only microtidal. Their largest effect is in areas within and adjoining zones of constriction, such as the channel, shoal, and island complex of the Preston River Delta, and the artificial exchange channel ("The Cut") between the ocean and the estuarine lagoon. They also transport sand along the western shore in areas close to "The Cut".

During winter floods, the Collie River transports and injects mud-laden freshwater into the estuarine environment, and transports sand along its channel floor. The river flood current is short-lived and localised only proximal to the mouth of the delta.

The main observed physical processes that transport, shape, and develop sediment bodies in the Leschenault Inlet estuary, and their effects in shaping the sedimentary environments and developing sediment types are summarised in Table 3.

A range of biota (Fig 3) and biological processes within Leschenault Inlet contribute to and structure the sediment. The shelly benthos are often environment-specific, and hence where incorporated into the sediments are indicative of formative environmental setting. The shelly benthos that contribute gravel-sized and sand-sized material to the sediment include gastropods, bivalves, and crustacean carapaces. The extant dominant molluscs that contribute to the sediment (after Semeniuk & Wurm 2000) and the ways in which they contribute are summarised in Table 4.

There are several main environmentally diagnostic molluscan assemblages contributing shell to the sediment: 1. a mixed molluscan assemblage that inhabited/inhabits the tidally flushed environments of the Preston River Delta and the tidal delta leeward of "The Cut"; 2. a *Tellina* (-*Spisula*) assemblage inhabiting the deep water central muddy basin; 3. a *Tellina-Nassarius-Bedeva* assemblage inhabiting seagrass-vegetated platforms; 4. *Hydrococcus* populations inhabiting tidal sandy beaches; 5. *Arthritica* populations inhabiting low tidal to shallow subtidal sand flats; 6. *Tellina* populations inhabiting shallow subtidal mud flats; and 7. *Acteocina* populations inhabiting intertidal mud flats.

Earlier in the Holocene, the molluscan assemblages were markedly different in composition (Semeniuk 1983, 1985), and some of these shells have been reworked and concentrated into the modern environment. In one instance, in the central basin, current winnowing has concentrated a gravel lag consisting of the large oyster *Ostrea angasi* that accumulated *ca* 4 000 years BP (3 960 ± 200 ^{14}C years BP; GX-10548; radiocarbon laboratory: Kreuger Enterprises Inc. Massachusetts).

Apart from shell contributions, biota are also involved in sedimentary processes in Leschenault Inlet in a number of ways (Fig 3):

1. Polychaetes thoroughly rework the substrate, burrow-structuring and bioturbating the sediment; sand, muddy sand and mud sediments are bioturbated, some forming burrow-structures 1 cm diameter in the central basin muds; *Capitella*, the sand worm, is abundant on sand flats and sand platforms, *Ceratonereis*, *Capitella*, *Nephtys* and *Scoloplos* are common on the platforms, and *Capitella*, *Nephtys* and *Scoloplos* in the muds of the central basin (Dürr & Semeniuk 2000; T A Semeniuk 2000).
2. The bivalve *Tellina deltoidalis* burrows and bioturbates the aquatic platforms and central basin sediments.
3. Seagrasses in the aquatic environment bioturbate and root-structure the sediment, and contribute detritus to the sediment.
4. Rushes and samphires bioturbate and root-structure the sediments on high tidal platforms, and contribute

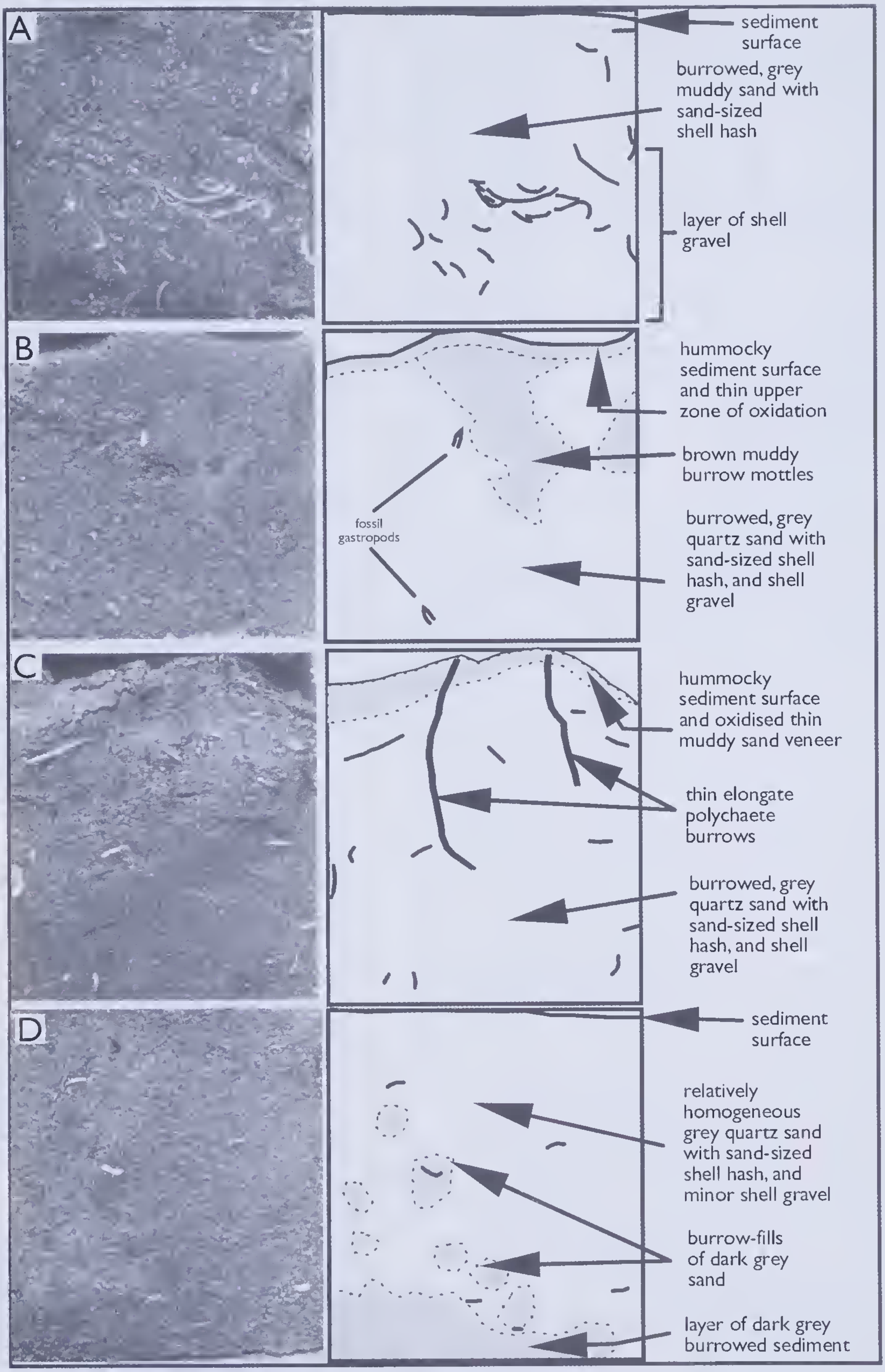

Figure 3. Photographs of sediment cores from Leschenault Inlet estuary, and accompanying line diagrams showing nature of sediments surface, sediment type, shelly components, bioturbation, and burrows. Length of cores 10 cm. **A:** burrowed grey muddy sand with sand-sized and gravel-sized molluscan shell; western platform. **B:** Burrowed quartz sand, with muddy sand mottles; shells are small gastropods reworked from earlier Holocene deposits; eastern platform. **C:** Burrowed quartz sand, with some thin elongate polychaete burrows; shell fragments are *Sanguinolaria*; eastern platform. **D:** Relatively homogeneous burrowed quartz sand, with small darker grey sandy burrow fills; minor scattered shell; eastern platform.

Table 3. Main physical processes in Leschenault Inlet estuary.

Process and main location	Main effects
wind-induced wave action on shores and east and west platforms	reworks sand on the eastern platform and generally fully removing any mud; reworks sediment on the western platform partly removing mud; erodes the sandy shores; erodes the small mud cliff shores; and shapes the surface of the eastern platform into sand waves and megaripple
wind-induced currents on east and west shores, and central basin	transports mud reworked and suspended by wave action into suspension to the northern basin and supratidal environments; transports and sorts sand, shapes the spitsand bars; winnows fine sediment leaving shell lags in the basin
storm waves on east and west shores, the north-facing sector of Collie River Delta, the northern supratidal flat, and the shallower parts of the central basin	builds storm beach ridges, transports shells onto the high tide and supratidal zone, winnows sediment along the shore and in deep water central basin, and erodes the small cliff shores
tidal flooding within the Preston River Delta and the artificial tidal delta	shapes and deposits sediment on the tidal delta and Preston River Delta
tidal current erosion and transport along the east and west shores	erodes and transports sand along the shore
tidal current deposition on the high-tidal platform and the northern mud basin and supratidal flat	accumulated mud onto the high tidal environments
riverine flooding at the mouth of the Collie River	injects riverine sand and mud into the estuary
wind erosion/ transport on the east and west located sandy beaches	develops small beach ridges and dunes that fringe the estuary shore, and build the spits and bars

detritus to the sediment.

5. Amphipods and insects burrow-structure and bioturbate the sediment of both the high-tidal platforms and the aquatic platforms.
6. Fish contribute to sedimentation processes in a number of ways: predating molluscs, forming gravel shell fragments by shell breakage; contributing shell grit and mud by defaecating ingested molluscs and associated sediment; and bioturbating the substrate through scavenging and hunting.
7. The large portunid crustacean *Portunus pelagicus*, similarly, is involved in the sedimentary processes by predating and breaking molluscs, forming gravel shell fragments, and by bioturbating the substrate through scavenging and burrowing.
8. Avifauna bioturbate the shallow subtidal sediments and tidal sediments through foraging and scavenging activities.

Sedimentary environments and sediment suites

The Leschenault Inlet environment contains a range of sediment types whose characteristics directly reflect the specific geomorphological settings described earlier (Fig 4); 1. central basin and northern basin suites; 2. eastern platform suite; 3. western platform/ramp suite; 4. high-tidal platform and northern supratidal flat suites; 5. low tidal flats; 6. spits, and bar-and-lagoon suite; 7. pocket beach suite; 8. Collie River Delta suite; and 9. Preston River Delta suite.

Spits, the bar-and-lagoon suite, and the pocket beach suite (see Fig 4C of Semeniuk & Meagher 1981) are too small to be shown in the map of Fig 4.

These sediment suites in their formative environment essentially form stratigraphic bodies (or shallow-depth sequences) with diagnostic geometry and lithologies. Though sedimentologically the suites are varied, there are dominant or characteristic sediments that typify them. The overall geometry of a suite and their characteristic sediments (without the sedimentary structural descriptors) are described in Table 5.

The full range of sediment types in the Leschenault Inlet area, further defined by their structure, fabric, texture, composition and shell content, are described in Table 6 below. Reiterating the provenance of the sand types, it is important to note that there are three types of sand in the sediments: 1. moderately rounded, fine to medium sand-sized quartz derived from the Mandurah-Eaton Ridge on the eastern shore; 2. rounded, fine to medium sand-sized quartz and carbonate derived from the Safety Bay Sand on the western shore; and 3. moderately rounded to angular, fine-, medium-, and coarse- sand-sized quartz of fluvial origin. In addition to the natural sediment suites described above, there are two locations where anthropogenic activities have resulted in an artificial riverine delta and an artificial flood tidal delta (*viz* the Preston River Diversion artificial delta suite and the artificial flood tidal delta suite).

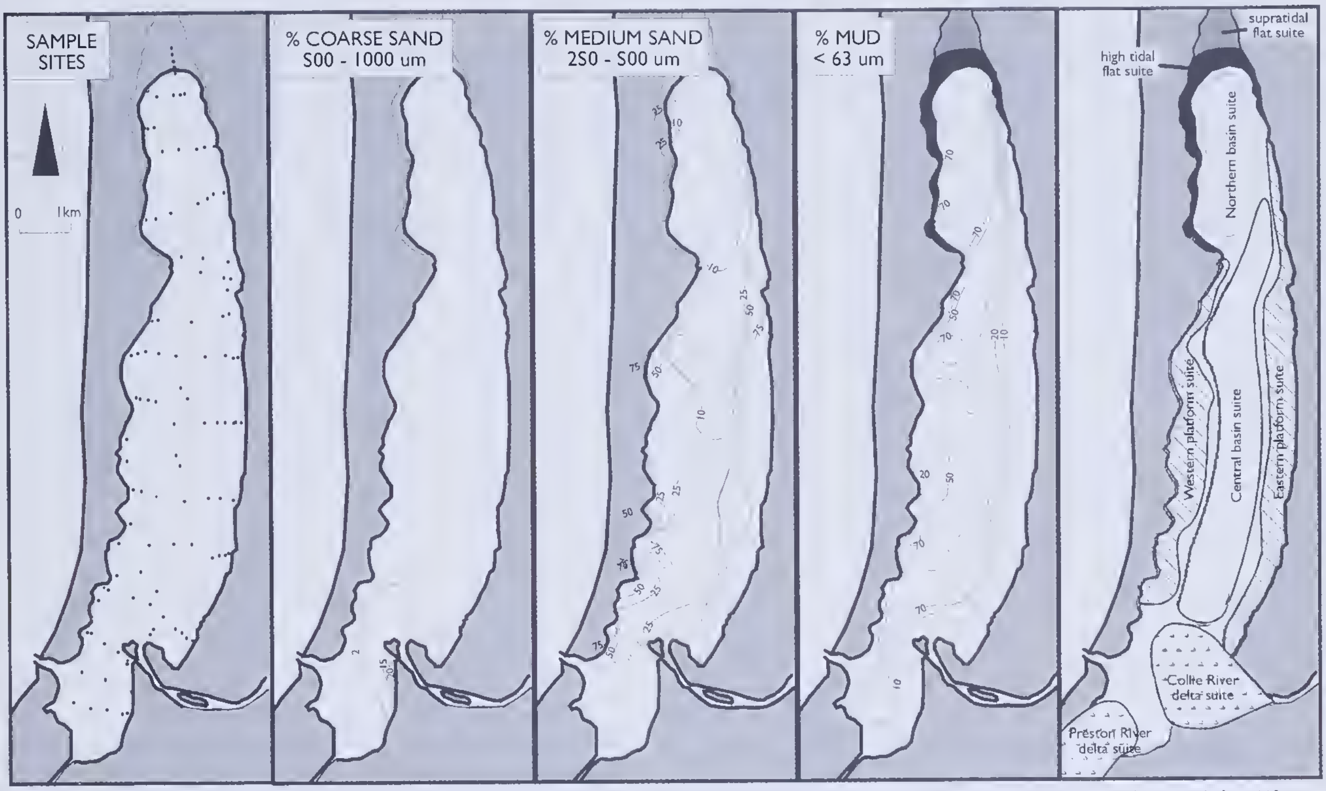

Figure 4. Maps showing sampling sites and the distribution of the coarse sand, medium sand, and mud in Leschenault Inlet (after Wurm & Semeniuk 2000). Final map shows sediment suites (or facies) based on grain sizes and geomorphic setting.

Table 4. Relationship between molluscs and sediment particles

Mollusc species	sediment particle generated
Acteocina sp	whole shell sand
Arthritica semens	whole shell sand
Bedeva paivae	whole shell gravel and fragments
Bembecium sp	whole shell gravel and fragments
Hydrococcus brazieri	whole shell sand
Nassarius (Parcanassa) burchardii	whole shell gravel and fragments
Tellina deltoidalis	whole shell gravel and fragments
Spisula (Notospisula) trigonella.	whole shell gravel and fragments
Fossil molluscs from earlier Holocene sediments	reworked whole shell gravel and fragments

Table 5. Stratigraphic attributes of the sedimentary bodies in the various suites

Sedimentary suite	shape of suite	characteristic sediments
central basin and northern basin	2 km wide ribbon	bioturbated mud and shelly mud; locally shell gravel
eastern platform	0.5 km wide wedge	quartz sand and shelly sand
western platform/ ramp	0.5 km wide wedge	muddy quartz/ carbonate sand, and shelly muddy sand
high-tidal platform	1 km wide ribbon	root-structured mud
northern supratidal flat	2 km x 2 km sheet	root-structured mud
low tidal flat sand	5-50 m wide ribbon	bioturbated mud varying to bioturbated
spits, bar-&-lagoon	small finger sands, and muddy lenses	quartz/carbonate sand, muddy sand and mud
pocket beach	thin ribbons or lenses metres wide	quartz/carbonate sand, quartz sand, mollusc grit
Collie River Delta	triangular wedge, 1 km x 1 km	quartz sand, muddy sand, mud and peat
Preston River Delta	lenses within a sheet, 2 km x 1 km	quartz sand, shelly quartz sand, muddy sand, mud

Longevity of sediment suites

Cores indicate that the various sediment suites are not just veneers in the estuarine lagoon, but are generally long term sedimentary features in the various subdomains of Leschenault Inlet (Figs 5-8). This is not unexpected, in that the controlling features developing the sediment suites in the environment are long-term stable geomorphic entities or on-going sedimentologic processes. The Pleistocene quartz sand ridge, for instance, has been a long term feature throughout the Holocene, so that it may be anticipated that that it has supplied quartz sand to the eastern platform throughout the history of the estuary. Being subject to wave trains generated by the sea breezes that would have existed throughout the Holocene, the eastern platform thus has persisted as a relatively mud-free sand platform for the duration of the estuarine conditions existing there. In the same way, the barrier dune complex that initially barred the estuarine lagoon has been a quartz/carbonate sand barrier from the onset, and has supplied this sand type to the western platform/ramp throughout the Holocene, whenever there was a western platform/ramp, or whenever a parabolic dune transgressed the width of the barrier and spilled over into the estuary. Similarly, deep water basins today, and their sediment-filled or shoaled equivalents (*viz* the northern basin and the northern supratidal flat), being deep water areas, or formerly deep water areas, and hence below base, have been long term sites for mud accumulation.

The stratigraphic cores from the northern supratidal flat, the northern basin, the eastern platform and the western margin of the western platform show that each sedimentary suite has been extant as a long term feature within the Leschenault Inlet environment, albeit with a variable sea-level history.

Sedimentological and stratigraphic evolution

The sedimentological history and stratigraphic evolution of the Leschenault Inlet system is described and discussed as follows: 1. the sedimentological/stratigraphic evolution of the system at the largest scale, *viz* the relationship of the sediments of the barrier dune to those of the estuarine lagoon; 2. the smaller scale stratigraphic interactions and relationships between the sediments of the barrier dune and estuarine lagoon; 3. small scale relationships within the deltas, and 4. the effect of a variable Holocene sea-level history on the stratigraphic evolution, and reconstruction of estuarine geomorphology over the Holocene.

Large scale relationships

The large scale sedimentary patterns and Holocene stratigraphic relationships within the Leschenault Inlet estuary are relatively simple (Figs 2 & 5): a shore-parallel wedge of sand reworked from Pleistocene landforms is onlapped by basin mud of the central estuarine lagoon, a

Table 6. Description of sediments with the various sedimentary suites.

Sediment type	Source of sedimentary particles; origin of sediment type
Central basin suite	
structureless to bioturbated mud	phyllosilicate clay, silica and carbonate mud transported by suspension; carbonate mud (silt-sized) also formed *in situ*; organic matter and detritus from aquatic plants, including silica silt from diatoms
structureless to bioturbated shelly mud	as above, but with shell from resident benthos
structureless to bioturbated sandy mud	as for the mud above, but with quartz and carbonate sand as grainfall from aeolian suspension
structureless to bioturbated shelly, sandy mud	source and origin as above, but with shell from benthic fauna
shell gravel	winnowed deposit of molluscan shell forming gravel lag pavement
Northern basin suite	
structureless to bioturbated mud	phyllosilicate clay, silica and carbonate mud transported by suspension; carbonate mud (silt-sized) formed *in situ*; organic matter and detritus contributed by aquatic plants
structureless to bioturbated shelly mud	mud as above, but with shell contributed by resident benthos
structureless to bioturbated shelly mud	mud as above; with winnowed local shell lags from resident fauna
Eastern Platform suite	
structureless to bioturbated quartz sand	sand eroded from eastern shore, bioturbated by benthic fauna
structureless to bioturbated shelly quartz sand	sand as above, with shell from local fauna concentrated in pockets and lenses
structureless to bioturbated muddy quartz sand	sand eroded from east shore, mud transported in suspension into site; detritus and organic matter from vegetation; bioturbated by benthos
structureless to bioturbated shelly and muddy quartz sand	sediment as above; shell from resident fauna; bioturbated by benthos

Table 6 Continued. Description of sediments with the various sedimentary suites.

Sediment type	Source of sedimentary particles; origin of sediment type
shell gravel	shell from local fauna; concentrated by winnowing
Western Platform/ramp suite	
structureless to bioturbated quartz and carbonate sand	sand eroded from western shore, bioturbated by benthic fauna
structureless to bioturbated shelly quartz and carbonate sand	sand as above; shell from resident fauna, bioturbated by benthos
structureless to bioturbated muddy quartz and carbonate sand	sand eroded from west shore, mud transported by suspension into site; bioturbated by benthic fauna
structureless to bioturbated shelly, muddy quartz and carbonate sand	sediment as above; detritus and organic matter from aquatic vegetation, shell from resident fauna; bioturbated by benthos
structureless to bioturbated sandy mud and muddy sand	phyllosilicate clay and carbonate mud transported by suspension; carbonate mud (silt-sized) also formed *in situ*; organic matter and detritus contributed by aquatic plants; quartz and carbonate sand contributed as grain fall from aeolian suspension
High-tidal platform and northern supratidal platform suites	
bioturbated and root-structured mud	phyllosilicate clay, and silica and carbonate mud transported by suspension; organic matter and detritus from aquatic plants; structured by fauna and vegetation
bioturbated and root-structured shelly mud	as above, but with shell deposited by storms and concentrated locally by winnowing
bioturbated and root-structured sandy mud	as above, with aeolian contribution of sand
bioturbated shelly, sandy mud	as above; shell from fauna
Low tidal flat suite	
bioturbated mud	mud transported shoreward from platform, or eroded from high-tidal mud platform; local shell contribution; reworked by biota
bioturbated sand	sand transported shoreward from platform, or eroded from adjoining upland dunes; local shell contribution; reworked by biota
Spit, and bar-and-lagoon suite	
structureless to bioturbated sand	dune sand eroded from west shore forming spits, structured by biota
laminated sand	dune sand eroded from west shore forming spits; reworked by waves and currents along beach shore
root-structured mud varying to structureless to bioturbated mud	phyllosilicate clay transported by suspension into lagoons leeward of spits and bars; structured and bioturbated by vegetation
root-structured, to bioturbated to structureless muddy sand varying to sandy mud	phyllosilicate clay transported by suspension into lagoons leeward of spits and bars; structured by vegetation; sand contributed by sheet wash from adjoining dunes, or as grain fall from aeolian suspension
Pocket beach suite (see Fig 4C of Semeniuk & Meagher 1981)	
laminated quartz sand and shelly sand	sand eroded from eastern shore, reworked in a tidal pocket beach
laminated quartz and carbonate sand and shelly sand	sand eroded from western shore, reworked in a tidal pocket beach
mollusc grit, to mollusc and quartz sand	quartz eroded from the shore; small gastropods and bivalves reworked and concentrated by wave action and storms on pocket beaches of east and west shores

Table 6 Continued. Description of sediments with the various sedimentary suites.

Sediment type	Source of sedimentary particles; origin of sediment type
Collie River Delta suite	
structureless and bioturbated quartz sand	riverine sicilic sand transported into delta; structured by biota
structureless to bioturbated shelly quartz sand	riverine sand transported into delta; shells from resident fauna or transported from adjacent environments; structured by biota
structureless to bioturbated shelly, muddy quartz sand	riverine sicilic sand and phyllosilicate clay and silica mud transported and mixed into delta; shells from resident fauna or transported from adjacent environments; structured by biota
laminated quartz sand	riverine sicilic sand transported into delta, structured by wave reworking
structureless to bioturbated muddy sand	phyllosilicate clay and riverine sicilic sand and mud transported into delta and mixed; structured by biota
structureless mud	mud as above, transported into delta
root- and burrow-structured mud	mud, as above, structured by biota
peat	accumulation of vegetation detritus
peaty sand	accumulation of vegetation detritus, mixed with sand within deltas
Preston River Delta suite	
structureless to bioturbated quartz sand	riverine sicilic sand transported into delta; structured by biota
structureless to bioturbated shelly quartz sand	riverine sicilic sand transported into delta; shells from resident mixed molluscan fauna or transported from adjacent environments; structured by biota
structureless to bioturbated shelly, muddy quartz sand	riverine sicilic sand and phyllosilicate clay and silica mud transported and mixed into delta; shells from mixed molluscan fauna or transported from nearby environments; structured by biota
laminated quartz sand	riverine sand transported into delta, structured by physical reworking
structureless to bioturbated muddy sand	phyllosilicate clay and silica mud, and riverine sicilic sand transported into delta and mixed; structured by biota
root-structured and burrow-structured mud	phyllosilicate clay and silica mud transported into delta; structured by biota
structureless mud	mud as above, transported into delta
peat	accumulation of vegetation detritus
peaty sand	accumulation of vegetation detritus, mixed with sand within delta
Preston Diversion Artificial Delta suite	
structureless to bioturbated quartz sand	riverine sicilic sand transported into delta; structured by biota
structureless to bioturbated shelly quartz sand	riverine sicilic sand transported into delta; shells from resident fauna; structured by biota
structureless to bioturbated muddy sand	phyllosilicate clay and silicic mud, and riverine sicilic sand transported into delta and mixed; structured by biota
structureless to bioturbated shelly, muddy quartz sand	sediment as above; shells from resident fauna; structured by biota
Artificial tidal delta suite	
structureless to bioturbated quartz and carbonate sand	sand eroded from the barrier dune, mobilised by oceanic waves, and transported into tidal delta on flood tides; bioturbated by benthic fauna
laminated to burrow-structured quartz and carbonate sand	sand as above, physically reworked to form lamination, and weakly burrowed by fauna

shore-parallel linear barrier dune complex bars and retrogrades over sediments of this estuarine lagoon; deltaic complexes invade the southern estuary, with the Collie delta recording a deltaic sand wedge capped by muddy sediments prograding into the estuarine lagoon, and the Preston River delta recording a tidal-deltaic system of shifting shoals, and intervening mud deposits.

The barrier and its lagoon have been extant during the middle to late Holocene for at least the past 7 000 years (Semeniuk 1985). The sheltered interior of the estuarine lagoon is accumulating mud, muddy sand, and locally sand, with estuarine shelly equivalents of these sediments. These sediments, referred to the Leschenault Formation, bear imprint of estuarine lagoonal conditions, as dark grey, or iron-sulphide pigmented, or bioturbated, or (estuarine) shelly sediments. To the east, these sediments either onlap a hinterland comprised of Pleistocene sediments, or onlap sediments derived from this Pleistocene basement, or interfinger with sediments derived from this Pleistocene basement. To the west, the barrier dune complex is comprised of a ribbon of white to cream quartz/carbonate sand, referred to the Safety Bay Sand. This barrier dune has been retreating eastwards over the estuarine sediment throughout the Holocene. The encroachment of barrier into the estuarine lagoon is through a staggered series of parabolic dune incursions that spill over into the estuary. Thus, at the largest scale, as a result of the retreat of the Holocene barrier, the Leschenault Formation sediments occupy the surface environments and underlie the extant estuarine lagoon, the Safety Bay Sand of the barrier dune overlies Leschenault Formation of the former wider estuarine lagoon, and the Leschenault Formation is exposed from under the seaward front of the retreating barrier (Semeniuk 1985).

With the net northwards transport of mud under influence of wind-driven currents, there is a general accumulation of mud in northern parts of the estuary that has resulted in the development of the expansive subtidal to supratidal mud deposits (the northern basin grading to the broad mud-underlain tidal flats, grading to the supratidal flats), and tidal deposits that developed in lee of the barrier to the northwest of the estuary (Fig 5 Transects 1 & 2, Fig 6 Transects A & B). Thus in an overview, the mud ribbon occupying the environment of Leschenault Inlet is asymmetrical, occurring in the central basin axis, but thickening to the north and northwest, and forming emergent tidal to supratidal surfaces to the north and northwest.

Smaller scale relationships

At the smaller scale, in contrast to the Pleistocene-based landforms of the eastern ridge and eastern shore, along the west coast of the estuary, because the barrier dune system is dynamic with staggered dune encroachments, the stratigraphic relationships between Safety Bay Sand dune sands and Leschenault Formation estuarine sediments are more complex (Figs 5 & 6; and Fig 5 of Semeniuk & Meagher 1981). Locally, mobile parabolic dunes rapidly and directly spill over into the estuary, forming a sandy apron in the aquatic environment, and here white Safety Bay Sand is transformed into grey Leschenault Formation sand. Lateral to this stratigraphic situation, muddy sediments of the Leschenault Formation accumulate, and later to be buried by an encroaching dune; here, white Safety Bay Sand overlies dark grey Leschenault Formation mud and/or muddy sand.

The staggered dune encroachment into the estuarine lagoon, with the laterally alternating fingers of dune sand and sheltered corridors with muddy accumulations develop a variable inter-digitating and complex interface between Safety Bay Sand and Leschenault Formation. Four types of stratigraphic sequences are generated within the Leschenault Formation at this interface with Safety Bay Sand: 1. sand aprons fronting estuary-encroaching dune tips; 2. muddy embayment fills between dune fingers; 3. the spits and bar-and-lagoon complexes; and 4. platforms and ramps extensive along the western estuary.

The Safety Bay Sand and Leschenault Formation interface is related to the position of high tide, and with the complex sea-level history in this area, this interface is variably located vertically (as will be discussed below).

Smaller scale relationships within the deltas

The gross stratigraphic array within the Collie Delta consists of deltaic sand prograding over estuarine basin mud (Fig 7), recording a deltaic wedge of sand capped by muddy sediments prograding into the estuarine lagoon. The smaller scale stratigraphic features within the delta include: 1. layered sand, muddy sand and mud in abandoned channels and inter-chenier swales in the upper deltaic sequences, correlating with the subaerial part of the delta; 2. shoestrings of sand (cheniers) interspersed with muddy sediments, correlating with the storm influenced subaerial part of the delta; and 3. ribbon and shoestrings of mud, representing abandoned channel-fills; the contact of these channel-fills with the adjoining sediments is erosional. The gross stratigraphic array within the Preston River Delta consists of lenses of shelly sand interlayered with muddy sand and mud (Fig 8), recording a tidal-deltaic system of shifting shoals, and intervening mud deposits. The fan delta in the north of the delta complex could not be sampled as it had been destroyed by earthworks in the 1960s. The smaller scale stratigraphic features within the delta include: 1. a central core of layered sand, shelly sand, muddy sand, flanked or capped by wedges or sheets of mud, correlating with a record of shoaling from shallow subtidal to high intertidal; 2. local lenses of emergent sand, recording a shoaling history from subtidal to supratidal; and 3. ribbons and shoestrings of mud, representing abandoned channel-fills.

Effect of variable Holocene sea-level history on evolution of stratigraphy

The sea level has been variable in the Leschenault Inlet area over the Holocene (Semeniuk 1985; Searle & Semeniuk 1986). Relative sea level was 2-3 m lower than present between 7 000-4 500 years BP, rising rapidly to a relative position 3-4 m higher than present between 4 500 and 3 500 years BP, and progressively falling to its current level from *ca* 2 800 years BP to the present. The relative sea level fluctuations had an effect on sedimentation and the development of sedimentary suites and coastal landforms in the Leschenault Inlet area (Fig 9). These effects are

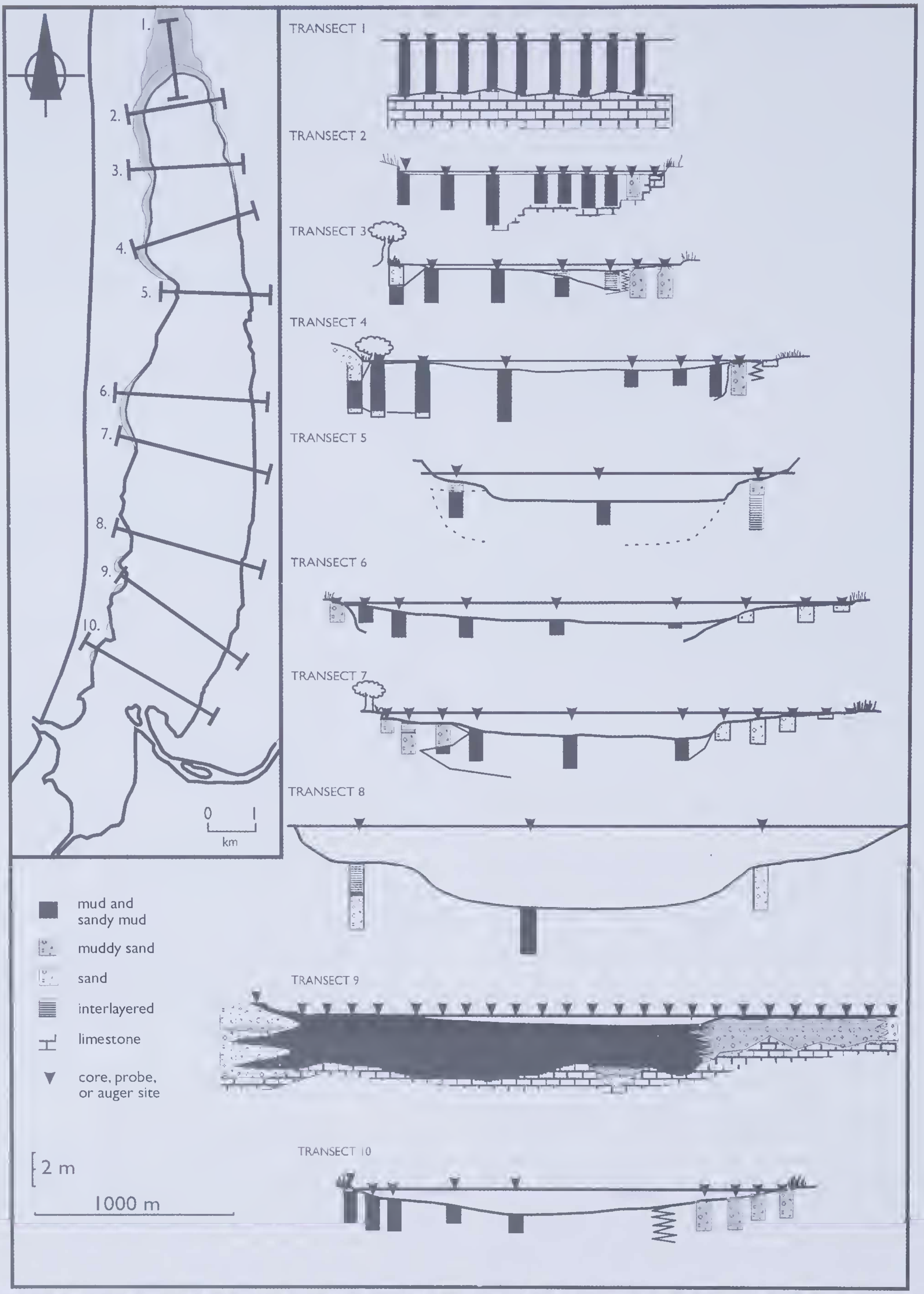

Figure 5. Various stratigraphic profiles across Leschenault Inlet, showing mud-dominated sections (central basin, north-western section, northern basin, and northern tidal to supratidal flats), and sandy to muddy sand margins.

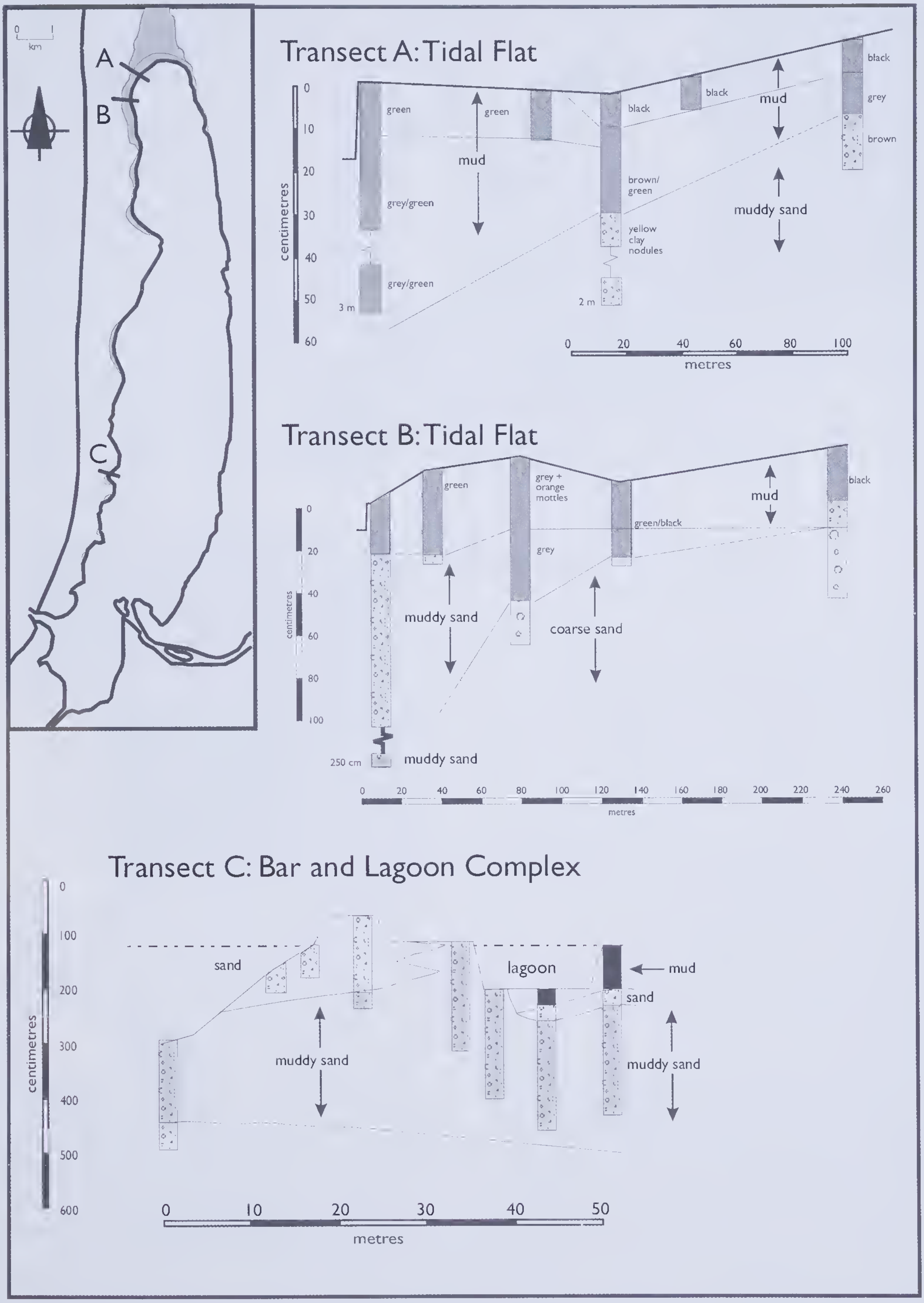

Figure 6. Various stratigraphic profiles across Leschenault Inlet showing a mud-dominated tidal flat sequences, and typical stratigraphy of a bar-and-lagoon complex.

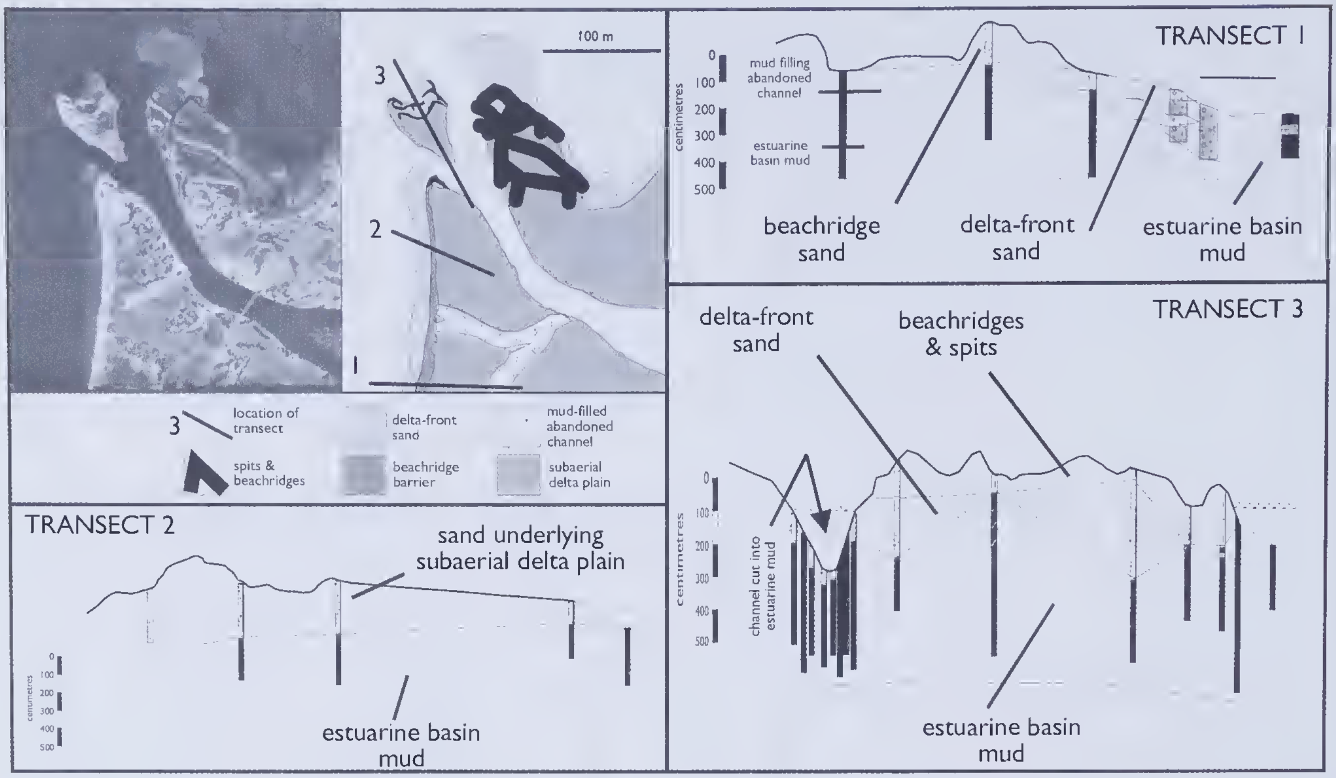

Figure 7. Aerial photographs geomorphic map, and stratigraphic profiles showing the anatomy of the Collie River delta. Interpretation of the formative sedimentary environment of the various sediment units are annotated on the cross-sections.

described for the various sedimentary environments within a framework of three stages of sea level positions *viz* Stage 1: sea level 2-3 m lower than present; Stage 2: sea level 3-4 m higher than present, and Stage 3: sea level at its present position. As will be described below, some of the details of the sedimentation and geomorphic response to a varying sea level have been documented in parts of the western platform, the eastern shore, and the central basin.

However, the details of the response of the sedimentation and coastal geomorphology to a varying sea level in this estuarine lagoonal setting must await further research. Some features of interest in this regard include, for instance, the sedimentation patterns in the deltas, the development of the spits, the bar-and-lagoon systems bordering a shallow then deeper estuarine lagoon, the response of biotic assemblages in terms of changing molluscan shell assemblages, and the mud budget within the system (*i.e.* its patterns of deposition, reworking, redispersal and redeposition).

During Stage 1, a barrier dune retreating over estuarine environments was already extant, as preserved in dune sand (Safety Bay Sand) overlying estuarine sediment (Leschenault Formation) with the stratigraphic interface located some 2-3 m below present sea level under the present barrier dune (Fig 8). Complications arising from the staggered dune encroachments into the estuary at this time are preserved as variable stratigraphic relationships between Safety Bay Sand and Leschenault Formation (*viz* thick dune sand on grey estuarine sand; thick dune sand on thick dark grey estuarine mud; thick dune sand on interlayered estuarine sand, muddy sand and mud; *cf* Semeniuk 1983).

The present central basin floor lies *ca* 2 m below sea level. Oyster shell lags on the surface dated at *ca* 4 000 years BP indicate that the mud floor probably had vertically accreted to this level *before* sea level reached the Stage 2 highstand, and that it had accreted to a level commensurate with Stage 1 sea level, and therefore that this surface was tidal or supratidal some 4 000 years BP.

For the eastern shore, for Stage 1 sea level, the surface of an eastern platform, initially developed as a wave-built structure which would have stood 2-3 m lower than its present surface. This surface would have since been buried by sand reworked to build the eastern platform structures during the higher and the present sea level stands of Stage 2 and Stage 3, respectively (see below).

Evidence for Stage 2 high-stand sea-level history is preserved in three relict estuarine sedimentary situations: as a relict western platform, as a relict eastern platform, and as relict shell beds in the central basin. For the relict western platform, estuarine shell bearing sand is preserved 1-2 m above sea level locally along the shore between the barrier dune and the estuary, indicating during the 3-4 m sea-level highstand, shelly sand beds formed on a subaqueous wave-planated dune sand terrain. Much of this stratigraphic evidence, however, has since been buried or erased by mobile sands. The evidence for the Stage 2 sea-level highstand is better developed on the eastern shore, because the ancestral sand ridge there was not dynamic and did not erase the record. Here, the eastern platform formed during the 3-4 m sea-level highstand is preserved as an elevated platform 1-2 m above present sea level (this surface would have been 1 m below sea level at the time of the highstand) underlain

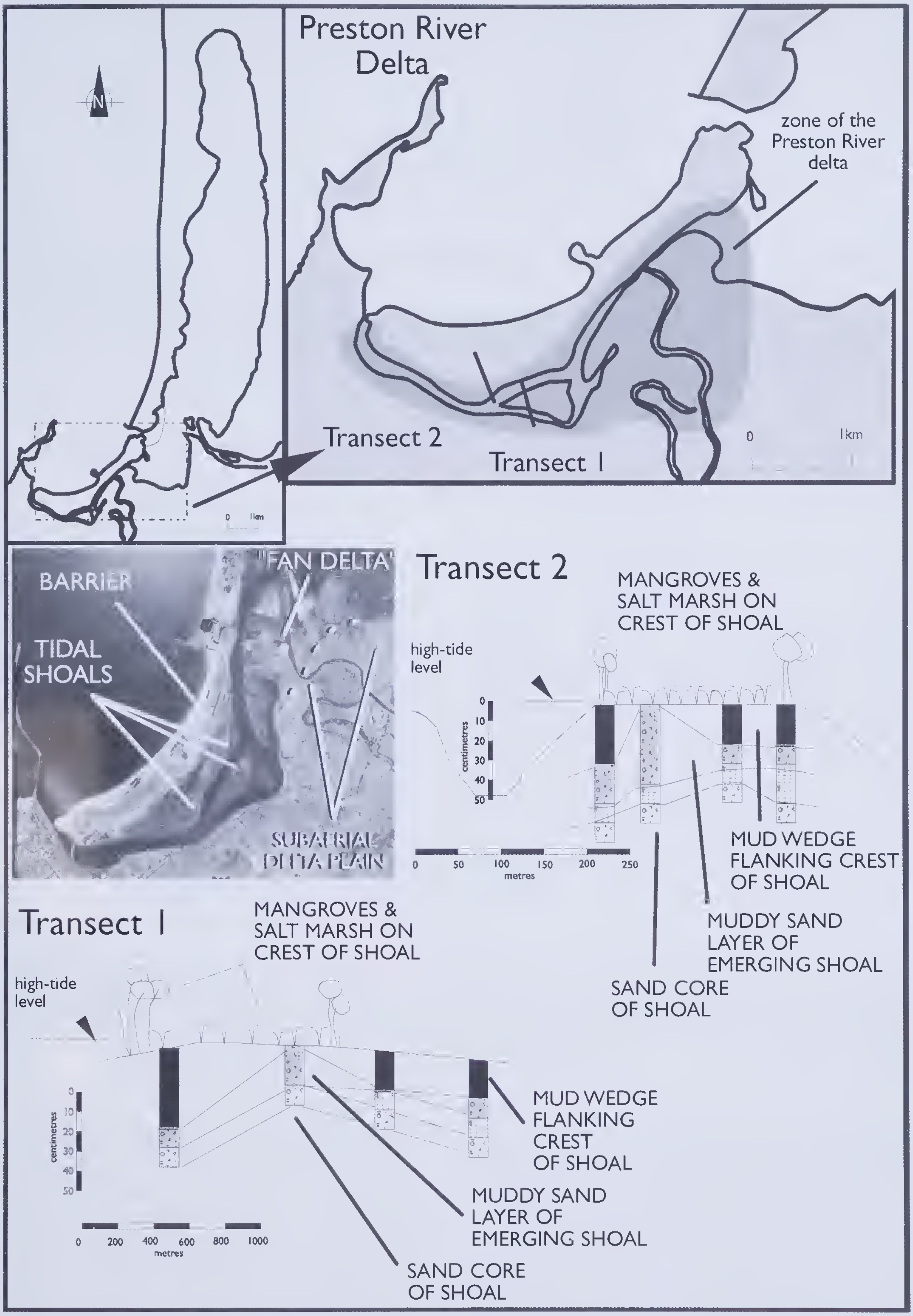

Figure 8. Aerial photograph, geomorphic map, and stratigraphic profiles showing the anatomy of the Preston River delta. Interpretation of the formative sedimentary environment of the various sediment units are annotated on the cross-sections.

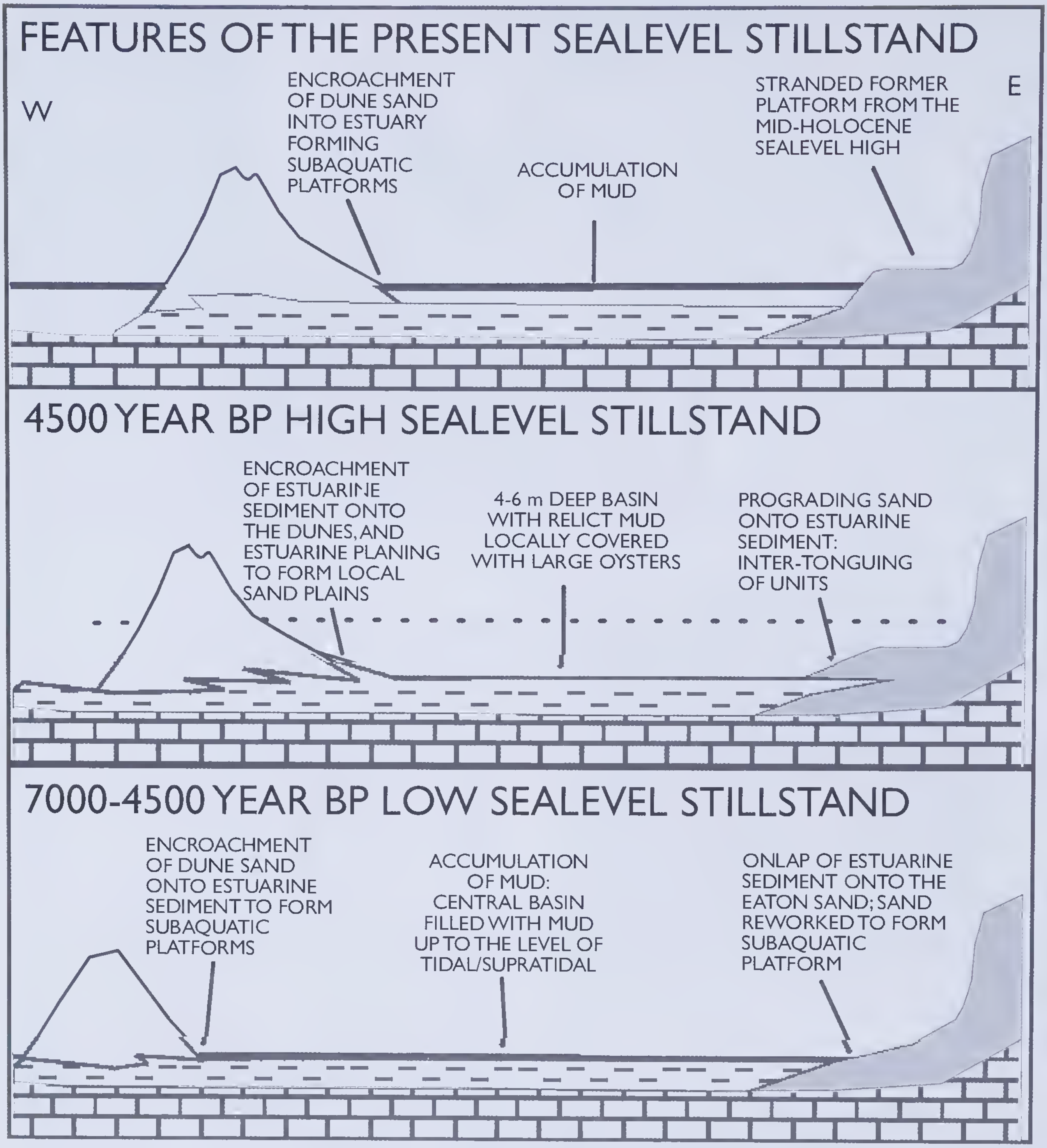

Figure 9. Depositional processes operating in Leschenault Inlet at the various still-stands of Holocene sealevel.

by structureless quartz sand. The sediments are free of estuarine shell (but this is not unexpected, as the equivalent sediment under the modern eastern platform are quartz rich, shell depauperate, and the stranded eastern platform since the sea-level fall to present levels has become a paperbark vegetated freshwater wetland, with peaty soils and acidic groundwater, with the attendant dissolution of any minor shells that have been present). Thus, the sedimentation event along the eastern shore during the Stage 2 sea-level highstand was reworking of the Mandurah-Eaton Ridge, and ongoing development of a higher level eastern platform underlain by quartz sand. The interlocking, of muddy sand and sand illustrated on the eastern shore at the 4 500 BP high sealevel stand (Fig 9) is preserved as thin beds of slightly muddy sand *under* the eastern platform at depth of 2m below present sea level.

With the apparently abrupt rise in relative sea level from 2-3 m below present level to 3-4 m above present level, in the central basin setting, the mud floor of a once high-tidal to supratidal surface would have been fairly rapidly inundated and placed below the zone of any wave reworking. In effect, the basin floor would have become a relict inundated high-tidal to supratidal surface and sedimentologically inactive. This mud surface, in at least 5 m of water, was the habitat for the large oyster *Ostrea angasi*. Thus, the sedimentation event in the central basin during the Stage 2 sea-level highstand was development of oyster shell beds.

With sea level at its present position (Stage 3), sedimentation involves the following main events: 1. development of the eastern platform at a new level related to the current sea level; 2. ongoing development of the western platform/ramp as parabolic dunes continue to be developed and to encroach into the estuary; 3. development of spits, evolving to bars and associated lagoons along the crenulate western shoreline; 4. development of the high-tidal platform through tidal mud accretion; 5. winnowing of mud from the subaquatic platforms and the central basin, and its transport via net northwards current drift into the northern basin; 6. shoaling of the northern basin to develop the northern supratidal flat; 7. injection of fluvial sand and mud into the estuary to develop the deltas; and 8. tidal reworking of the Preston River Delta to develop tidal-dominated estuarine landforms.

References

Anon 1975 Climatic Averages of Western Australia. Bureau of Meteorology. Australian Government Printing Service, Canberra.

Brown R G, Treloar J M & Clifton P M 1980 Sediments and organic detritus in the Peel-Harvey estuarine system. Bulletin 90. Department of Conservation & Environment, Perth.

Dürr V & Semeniuk T A 2000 Long-term spatial dynamics of polychaetes in Leschenault Inlet estuary. Journal of the Royal Society of Western Australia 83: 463-474.

Gentilli J 1972 Australian Climatic Patterns. Nelson Press, Melbourne.

Hayes M D 1975 Morphology of sand accumulation in estuaries: An Introduction to the Symposium. In: Estuarine research Vol. II: Geology and Engineering (ed L E Cronin). Academic Press, New York, 3-22.

Koppen W 1936 Das Geographische System der Klimate, 1, C. In: Handbuch der Klimatologie (eds W Koppen & R Geiger). Gebruder Borntraegar, Berlin.

Powers M C 1953 A new roundness scale for sedimentary particles. Journal of Sedimentary Petrology 23:117-119.

Searle D J & Semeniuk V 1985 The natural sectors of the Rottnest Shelf Coast adjoining the Swan Coastal Plain. Journal of the Royal Society of Western Australia 67:116-136.

Semeniuk C A & Semeniuk V 1990 The coastal landforms and peripheral wetlands of the Peel-Harvey estuarine system. Journal of the Royal Society of Western Australia 73:9-21.

Semeniuk T A 2000 Small benthic crustacea of Leschenault Inlet estuary. Journal of the Royal Society of Western Australia 83: 429-442.

Semeniuk V 1983 The Quaternary stratigraphy and geological history of the Australind-Leschenault Inlet area, Western Australia. Journal of the Royal Society of Western Australia 66:71-83

Semeniuk V 1985 The age structure of a Holocene barrier dune system and its implication for sealevel history reconstructions in south-western Australia. Marine Geology, 67:197-212

Semeniuk V 1995 New Pleistocene and Holocene stratigraphic units in the Yalgorup Plain area (amended from Yoongarillup Plain), Southern Swan Coastal Plain. Journal of the Royal Society of Western Australia 78:67-79

Semeniuk V 1997 Pleistocene coastal palaeogeography in south-western Australia - carbonate and quartz sand sedimentation in cuspate forelands, barriers and ribbon shoreline deposits. Journal of Coastal Research 13:468-489.

Semeniuk V & Meagher T D 1981 The geomorphology and surface processes of the Australind-Leschenault Inlet coastal area. Journal of the Royal Society of Western Australia 64:33-51

Semeniuk V & Searle D 1986 Variability of Holocene sealevel history along the south-western coast of Australia - evidence for the effect of significant local tectonism. Marine Geology 72:47-58

Semeniuk V & Wurm P A S 2000 Molluscs of the Leschenault Inlet estuary - their diversity, distribution, and population dynamics. Journal of the Royal Society of Western Australia 83: 377-418.

Wentworth C K 1922 A scale of grade and class terms for clastic sediments. Journal of Geology 30:377-392.

Wurm P A S & Semeniuk V 2000 The Leschenault Inlet estuary - its physical features and habitats for benthic fauna. Journal of the Royal Society of Western Australia 83: 229-250.